A Doppler Smoothing Filter using Carrier Phase and Application to RTK

Byung-Hyun Lee, Konkuk University, Korea  
Gyu-In Jee, Konkuk University, Korea  
Chan-Gook Park, Seoul National University, Korea

BIOGRAPHY

Byung-Hyun Lee is a Ph.D student in Konkuk University. He received his MS.c degrees at Konkuk University in 2009. He’s interested in Software GNSS receiver, GNSS modernization, precise positioning, and Anti-Jamming technique.

Gyu-In Jee is a professor of Electronics Engineering of Konkuk University. He received his Ph.D in System Engineering from Case Western Reserve University in 1989. His research interests include Indoor GPS positioning, Software GNSS receiver, GPS/Galileo baseband FPGA design, and Anti-Jamming technique.

Chan-Gook Park is a professor of School of Mechanical and Aerospace Engineering of Seoul National University. He received his Ph.D in Control and Instrumentation Engineering from Seoul National University in 1993. His research interests include the development of Inertial Navigation Systems, GPS/INS integration, low-cost IMU application, positioning for Ubiquitous Sensor Network and advanced filtering techniques.

ABSTRACT

Recently, in the field of ITS (Intelligent Transportation System), accurate and precise position of a vehicle in the street is more demanding. They want to know which lane a car is driving in. The GNSS RTK could provide this accuracy. But, in urban street, due to its environment, the conventional code and carrier based RTK can’t be a practical solution. The Doppler measurement from GNSS receiver could be considered as one more measurement to solve this problem.

A carrier smoothing of Doppler measurement using Kalman Filter is proposed in this paper. This carrier smoothing technique for Doppler measurement can improve Doppler measurement noise level, especially for low cost GNSS receiver. For more robust RTK float solution, this carrier smoothed Doppler measurement is included in double differenced RTK measurement and the velocity estimation performance is much improved. And the innovation and covariance of the smoothing filter is found to be efficient in detecting carrier cycle slip. Field test in urban area shows effectiveness of using carrier smoothed Doppler measurement in RTK for precise positioning of vehicle in the street.

INTRODUCTION

In order to get highly precise position in GNSS system, carrier phase measurements must be used. As known in [1], the resolution of carrier phase measurements is typically better than 0.1mm. However, so as to use this measurement, unknown integer cycles of carrier phase should be resolved. This unknown number is so called integer phase ambiguity.

In the open sky environment, ambiguity can be resolved and satellites are in line-of-sight well. But in urban case there are many problems. First, integer ambiguity is rarely resolved. Most land vehicles drive in urban area, and there’re many tall buildings. These cause severance of phase lock loop, and it appears as cycle slip. To use carrier phase measurement stably, continuity of phase tracking should be guaranteed. Second is multipath. Carrier phase measurements are robust to multipath. However code measurements have large multipath error, it is reflected to position error. But Doppler measurement has small influence by multipath than code measurement and is free from integer ambiguity.

Thus, Doppler is one of the necessary measurements for urban precise positioning. However, the noise level of Doppler measured by the low-cost GNSS receiver is worse than survey GNSS receiver.

Therefore, this paper proposes Doppler smoothing filter using carrier phase measurement to improve positioning performance in urban area.
BENEFITS OF DOPPLER MEASUREMENTS AND POSITION SMOOTHING FILTER

Conventional RTK use code and carrier phase measurement for precise positioning. Precise positioning is for survey land until now, so it is used in open sky environment. And for precise positioning, integer ambiguity should be resolved. It means navigation filter needs successive phase measurements. However urban area has frequent variation of visible satellites by buildings, so it is hard to measure phase measurements continuously. Thus fixed solution is rarely calculated in urban. It means conventional RTK is not practical solution in urban environment. In this paper, Doppler measurements are used for more robust and precise float solution.

Typically, users are moving vehicles in urban. So velocity is one of the important information. Taken together, we need reliable single-epoch measurements and that enhances performance of velocity estimation. And Doppler measurements are the meaning of amount of change. The equation is as below.

$$\lambda f^i_u = \hat{r}^i + \left( B_u - \hat{b}^i \right) + \hat{I}^i_u + \hat{T}^i_u + \delta \dot{V}^i + \varepsilon$$  \hspace{1cm} (1)

Where $\lambda$ is wavelength; $f^i_u$ is raw Doppler measurements of receiver $u$ from satellite $i$; $\hat{r}$ is geometric range rate; $B_u$ is receiver clock drift; $\hat{b}^i$ is satellite clock drift; $I^i_u$ is ionospheric delay rate; $T^i_u$ is tropospheric delay rate; $\delta \dot{V}^i$ is calculation error of satellite velocity; $\varepsilon$ is receiver noise.

And the physical expression is defined in equation (2).

$$\lambda f^i_u = h^i_u \cdot (v^i - V^i) + B_u + \xi$$  \hspace{1cm} (2)

Where, $h^i_u$ is LOS (line-of-sight) vector; $v^i$ is receiver velocity; $V^i$ is satellite velocity; $\xi$ is ionospheric, tropospheric delay rate, velocity error of satellite and receiver noise.

That is, Doppler measurement is direct measurement for velocity, and Doppler added navigation filter can improve performance of velocity estimation [2] and more accurate velocity makes state prediction improved.

And position smoothing filter [3] using Doppler measurement can reduce position error in urban (Figure 1). This smoothing filter use delta-position estimation.

In Ref. [3], delta-position was estimated by integrating Doppler measurements in order to lower noise level. The inputs of position smoothing filter are solution of navigation filter and delta-position and position smoothing filter is one of the fusion filter. This filter gives smoothing effect in position domain. Equation (3) shows double differenced Doppler measurement.

$$\rho^{k,j}_{i,j} = \left( h^k_{i,j} v^k - h^j_{i,j} v^j \right) + h^k_j v_j$$  \hspace{1cm} (3)

And equation (4) represent the term of user velocity of equation (3)

$$h^k_j v_j = \rho^{k,j}_{i,j} = \left( h^k_{i,j} v^k - h^j_{i,j} v^j \right)$$  \hspace{1cm} (4)

The left term of equation (4) means delta-position. That is, delta-position can be estimated using double differenced Doppler measurements directly. And errors of satellite and receiver are eliminated or reduced because it is double differenced Doppler measurement. Thus Doppler measurements of single-epoch can provide reliable delta-position.

DOPPLER SMOOTHING FILTER

If the quality of Doppler measurement is as much precise as carrier phase, then delta-position is accurate without Doppler smoothing filter. And almost precise positioning in urban area is for ITS (Intelligent Transport System). For the ITS, the price of receiver should be cheap. Unfortunately Doppler measurement measured by low cost receiver has low quality than survey receiver. Thus Doppler smoothing filter was proposed in order to enhance quality of Doppler.

Doppler measurement is the meaning of delta range. And there’s no integer ambiguity in time differenced carrier
phase which is the meaning of delta range too. So, Doppler measurement can be smoothed by carrier phase. Kalman filter is used as smoothing filter. The equation is as below

State prediction:

\[ \hat{x}_k^- = -x_{k-1} + \frac{2}{dt} (\Phi_k - \Phi_{k-1}) \]  

(5)

\[ \hat{P}_k^- = P_{k-1} + Q \]  

(6)

Measurement Update:

\[ K_k = \frac{P_k^-}{P_k^- + R} \]  

(7)

\[ \hat{x}_k^+ = \hat{x}_k^- + K_k (z_{dopp} - \hat{x}_k^-) \]  

(8)

\[ \hat{P}_k^+ = (1 - K_k) \cdot \hat{P}_k^- \]  

(9)

The benefit of Doppler smoothing is not only improving measurement quality but also cycle slip detection. Monitoring the difference between Doppler and time-differenced carrier phase is one of the most famous technique for cycle slip detection. Thus residuals of Doppler smoothing filter can be the input of cycle slip detection module.

**EXPERIMENTAL RESULTS**

The performance of Doppler smoothing filter was evaluated by applying to RTK. Figure 2 shows the outline of navigation system of in this paper.

![Figure 2. Outline of navigation system](image)

And the performance of velocity estimation and delta position estimation are the evaluation indices. Figure 3 and Table 1 show the performance of delta position and velocity estimation in static environment.

![Figure 3. Delta-position error in static](image)

<table>
<thead>
<tr>
<th>Table 1. Delta position and velocity error</th>
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<tbody>
<tr>
<td><strong>RMS</strong></td>
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<tr>
<td>Delta position [cm]</td>
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<tr>
<td>Velocity [cm/s]</td>
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</tbody>
</table>

According to the results, the performance of delta position and velocity estimation is improved using Doppler smoothing filter. This means the quality of Doppler measurements is improved by carrier phase measurement.

The followings are the results in urban area. In this dynamic environment, true position is unknown. Thus the performance was evaluated whether the results are in true lane or not by using precise map data and driving in same lane.

Figure 4 shows urban environment that surrounded by buildings and Figure 5 shows precise map data of test site. The magenta refers centerline.

![Figure 4. Test site (Urban)](image)
Table 2. Experiment environment

<table>
<thead>
<tr>
<th>Date</th>
<th>2011/03/21</th>
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<tbody>
<tr>
<td>Receiver</td>
<td>Reference: Novatel OEM-V</td>
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<td></td>
<td>Rover: U-blox AEK 4T</td>
</tr>
<tr>
<td>Baseline</td>
<td>15km</td>
</tr>
<tr>
<td>Performance analysis</td>
<td>Precise Map Data Driving twice in same lane</td>
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Figure 6 is the result of conventional RTK in open sky environment. In the open sky environment, the results of conventional RTK and position smoothing filter are in true lane. It means smoothed position which is calculated by Doppler measurement can be used as precise positioning in urban environment. And Figure 7 is the result of velocity estimation in urban area. In this figure, Doppler measurement added navigation filter can provide more reliable and stable velocity. Especially, after the lack of visible satellites is occurred, the estimated velocities are jumped. However the Doppler added navigation filter provides more accurate velocities.
Figure 7. Velocity results in urban area [without Doppler (left), Doppler added (right)]

Figure 8 shows positioning error of conventional RTK in urban. This area is surrounded by buildings so multipath caused this position error.

In this area, the true trajectory is on the first lane. But positioning error even out of street is occurred with conventional RTK.

Figure 9 is the result of smoothed position which is calculated by proposed Doppler smoothing filter.

Figure 8. Positioning results of conventional RTK in urban area (top) and its environment (bottom)

Figure 9. Positioning results of Doppler smoothing filter applied

By figure 9, proposed method enables to reduce position error, in other word, positioning performance is improved.
CONCLUSIONS

The conventional RTK cannot be a practical solution in urban area because it is hard to resolve integer ambiguity. In addition, the positioning error by multipath and cycle slips is significant problem too. But in normal condition, RTK float solution can provide lane identifiable performance, and position smoothing filter also can provide. There is positioning error, however, in urban area. Thus more improved position smoothing filter is needed. In this paper, in order to improve accuracy and availability in urban, position smoothing technique using smoothed Doppler measurement which is smoothed by proposed Doppler smoothing filter. Proposed Doppler smoothing filter using carrier phase improves delta position estimation. It means proposed method can improve the performance of position smoothing filter and can provide more available positioning results.

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